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Auto-Gopher-II – A wireline rotary-hammer ultrasonic drill that operates autonomously

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ABSTRACT

An important challenge of exploring the solar system is the ability to penetrate at great depths the subsurface of planetary bodies for sample collection. The requirements of the drilling system are minimal mass, volume and energy consumption. To address this challenge, a deep drill, called the Auto-Gopher II, is currently being developed as a joint effort between JPL's NDEAA laboratory and Honeybee Robotics Corp. The Auto-Gopher II is a wireline rotary-hammer drill that combines breaking formations by hammering using a piezoelectric actuator and removing the cuttings by rotating a fluted bit. The hammering is produced by the Ultrasonic/Sonic Drill/Corer (USDC) mechanism that has been developed by the JPL team as an adaptable tool for many drilling and coring applications. The USDC uses an intermediate free-flying mass to convert high frequency vibrations of a piezoelectric transducer horn tip into sonic hammering of the drill bit. The USDC concept was used in a previous task to develop an Ultrasonic/Sonic Ice Gopher and then integrated into a rotary hammer device to develop the Auto-Gopher-I. The lessons learned from these developments are being integrated into the development of the Auto-Gopher-II, an autonomous deep wireline drill with integrated cuttings and sample management and drive electronics. In this paper the latest development will be reviewed including the piezoelectric actuator, cuttings removal and retention flutes and drive electronics.

KEYWORDS: Planetary sampling, piezoelectric devices, wireline drill, life detection.

1. INTRODUCTION

A wireline deep drill called Auto-Gopher II is under development as a joint task by JPL's NDEAA group and Honeybee Robotics Corporation. The drill mechanism described in earlier publications [Badescu, 2017] is being developed for penetrating consolidated subsurface as both ice drill, with potential application to deep drilling at Europa or Enceladus, and soft rock drill, with potential application to Mars. The Auto-Gopher II wireline rotary hammer drill combines formation breaking using impacts generated by an ultrasonic actuator and cuttings removal using rotation and a fluted bit.

The drill system has a long cylindrical body and encloses the drill bit, hammer and rotary actuators, anchors, feed actuators, drive and communication electronics. It is suspended by a cable that provides power, communication, and has enough strength to support the weight of the drill and the cable. The drill will be lowered into the borehole using a set of anchors and will drill a predetermined incremental depth collecting the cuttings then will return to the surface to have the cuttings removed. The operation will be repeated until the desired penetration depth has been reached.

The hammering mechanism is based on the Ultrasonic/Sonic Drill/Corer (USDC) mechanism that has been developed as an adaptable tool for many drilling and coring applications [Bar-Cohen, 2001; Sherrit, 2000; Bao, 2003]. The USDC uses an intermediate free-flying mass or striker to transform high frequency vibrations of a piezoelectric transducer horn tip into lower frequency higher impact hammering of the drill bit. The USDC concept was used in previous tasks to develop an Ultrasonic/Sonic Ice Gopher [Badescu, 2006] and a rotary hammer device the Auto-Gopher-I [Badescu, 2011, Bar-Cohen and Zacny, 2009, Zacny, 2013]. The lessons learned from these developments are being integrated into the development of the Auto-Gopher-II, an autonomous deep wireline drill with integrated cuttings and sample management, drive and communication electronics and sensors.

Subsystems of the Auto-Gopher II wireline drill are being developed in parallel at JPL and Honeybee Robotics Ltd. This paper presents the development efforts of the piezoelectric actuator, drive electronics, and integration of the drill bit with the hammering actuator.

2. SYSTEM DESIGN

The basis for the current drill system design stems from Honeybee Robotics' independent previous planetary deep drill projects and joint JPL – Honeybee Robotics Auto-Gopher I and shallow drill designs, which demonstrated their functionality in gypsum and other materials numerous times. The layout of the current mechanical drill design is depicted in Figure 1 and the main components with a short description are shown in Table 1. Length of the drill as shown in Figure 1 is 3.9 m [152 in] with 101.6 mm [4 in] OD body. The current weight estimate of the drill is about 70 kg.

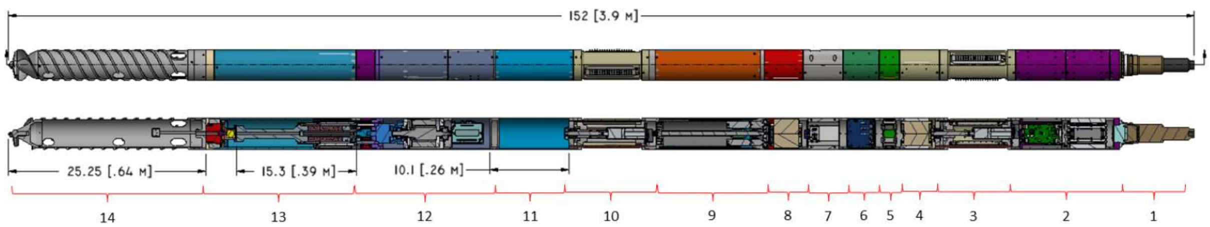


Figure 1: Drill system design configuration

Table 1: Drill system main components

Section #	Section names	Description
(1)	Cable Termination	Top Connectors for E-O signals, and strength member termination
(2)	Power Converters	Front-end converters for 300-360 VDC input stepped down to various intermediate buses
(3)	Top Anchor	Anti-torque and anti-preload system for nominal drilling operation
(4)	Top Anchor & Z1Controllers	Motor controllers for Z-stage and top set of Anchors
(5)	5V Power	POL power converters outputting 5 VDC
(6)	Data Media Converters & CPU	MAGBES, and CPU for drill's controls
(7)	Camera/Sensor	Includes borehole camera and AHRS sensor
(8)	Bottom Anchor & Z2 Controllers	Motor controllers for Z-stage and Anchors
(9)	Z-stage	Provides longitudinal movement and generates WOB
(10)	Bottom Anchors	Anti-torque and anti-preload system for inch-worming
(11)	Piezo Electronics	Consists of control and power electronics for Piezo Actuator
(12)	Auger Drive	Includes a BLDC motor, controller, and gear train
(13)	Thumper & Piezo Actuator	Mechanical shock generator for Auger/Bit & An ultrasonic percussion based hammer system
(14)	Auger/Bit	Full faced bit with Auger for sample cuttings collection

The drill is suspended by an umbilical cable that provides a 3-in-1 solution which is used as a medium to transfer data and power while also functioning as a tether supporting the weight of the drill payload which includes the drill itself, cable and sample on the auger flutes and bit. The cable termination provides the mechanical and electrical interface between the drill and the tether and was designed to support as much as 5kN force. Power converters transform the 360V DC voltage to various intermediate buses. The anchors were designed as self-contained modules to include their own actuators. They provide up to 8kN output force and can be synchronized together with the Z stage to provide the drill inchworm motion capability. Additionally, the high force capability of anchors and the Z-stage allow the drill to be unjammed in the borehole if necessary. The camera/sensor compartment includes a color CMOS camera and sensors for redundant slip detection. The thumper provides a single high impact to the top of the drill bit in case the bit gets stuck during drilling. It includes a series of high pull force magnets.

3. TRANSDUCER DEVELOPMENT

A piezoelectric actuator redesigned for this task includes alumina disks at the ends of the piezoelectric stack to insulate electrically the piezoelectric stack electrodes from the transducer horn, backing and stress bolt allowing the ground to float. These insulators were integrated to match the interface dictated by the whole system drill design. The actuator solid model is shown in Figure 2. A photograph of a first assembled actuator is shown in Figure 3 below. Preliminary actuator testing was performed using both laboratory drive electronics and the task developed drive electronics. An impedance spectra of the fabricated transducer is shown in Figure 4.

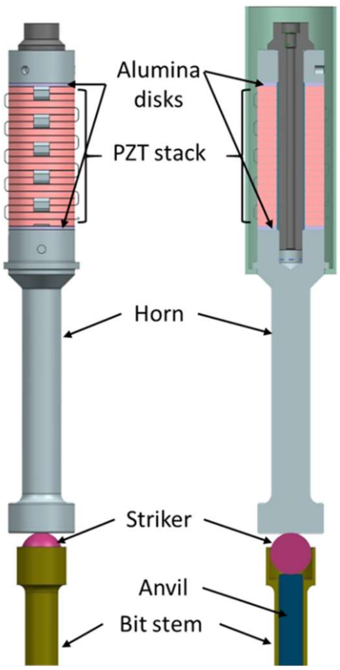


Figure 2: Piezoelectric transducer design integrated into a testbed

Figure 3: Testing of the fabricated piezoelectric transducer

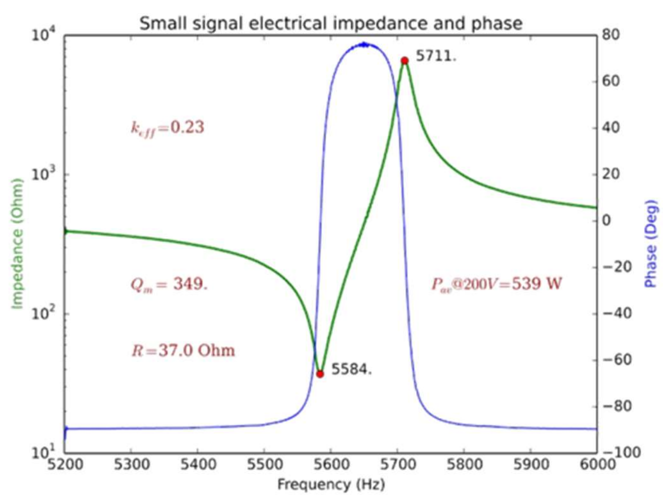


Figure 4: Transducer impedance spectra for small signal

The 5 kHz actuator and a testbed that was constructed allowed for the testing of the actuator performance with respect to the impact energy (Figure 5). The testbed includes a vertically mounted plate on which the actuator is mounted at the neutral plane flange. The testbed was updated to have the actuator mounted with the horn tip facing down to include a preload spring as it is in the drill system implementation. A solid rod is used as a bit replacement and was mounted between two high stiffness wave springs preloaded between two plate-mounted collars. The gap between the bit replacement and the striker could be adjusted to determine an optimal value where the striker reaches resonance.

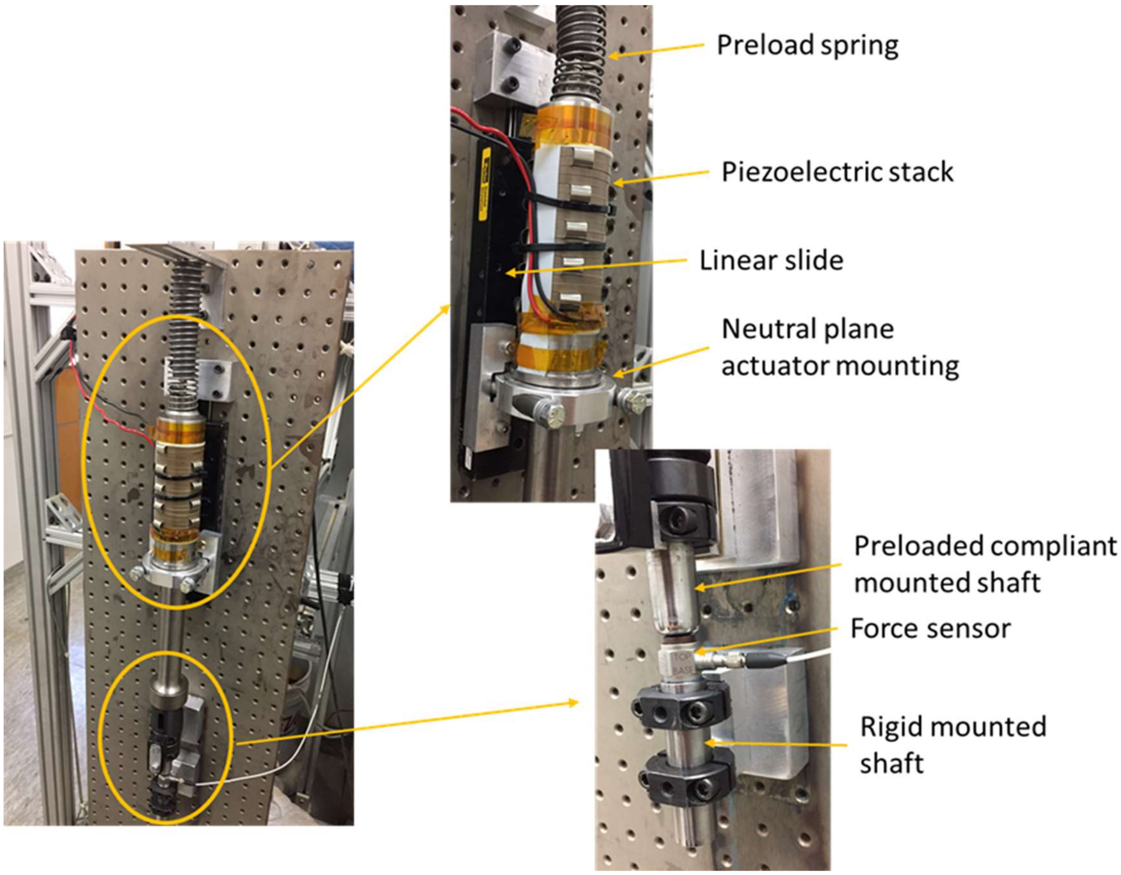


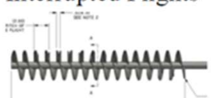
Figure 5: Piezoelectric actuator testbed

Two piezoelectric actuators were fabricated and tested; one used 5.1mm thick PZT rings and a second one used 6.35mm thick PZT rings. The larger thickness PZT rings were selected to accommodate the voltage supplied by the system without the need to use an intermediate transformer. Although the total length of the PZT stacks was the same for both actuators, the performance was not the same. The thicker PZT rings actuator was not able to bounce a 38mm diameter, 226g mass ball. A current investigation is underway to determine the reasons of the performance mismatch and possible solutions to mitigate the problem. In addition a noticeable decrease in the mechanical Q of the actuator was determined after initial testing and the source of the decrease is being investigated.

4. TRANSDUCER –DRILL BIT INTEGRATION AND ANALYSIS

Three sets of auger deigns were developed and tested at both Honeybee Robotics and JPL. Tests results at JPL were reported in previous publications. Table 2 below shows the three configurations tested at Honeybee and their test results. The decision was made to select the catch basket design configuration as it provides a higher effective cuttings retention capacity. The design was integrated with the striker of the piezoelectric transducer and an analysis was performed to evaluate the impact energy transfer to the brill bit – rock interface. The column Effective FF in Table 2 includes a form factor that takes into account the efficiency of the cuttings capacity to be filled with cuttings.

Table 2: Auger designs and parameters

Auger	Auger-bit assembly volume	Auger-bit assembly length	Drilled depth	Drilled volume (diam. = 10.8 cm)	Cuttings volume assuming FF=2.34 for ice	Cuttings capacity	Effective FF	Theoretical maximum drilling depth
	cc	cm	cm	cc	cc	cc		cm
Continuous Flight 	467	61.6	61.0	5579	13056	5112	2.55	24.1
Interrupted Flights 	532	61.6	61.0	5579	13056	5048	2.59	23.8
Long Catch Basket 	628	60.1	61.0	5579	13056	4952	2.64	22.8

To study the hammering behavior of the bit, a Finite Element (FE) model was established. An axisymmetric model that includes a steel ball having 38 mm (1.5 inch) diameter, drill bit and a block of rock was used (Figure 6). The real teeth of the bit are arranged in a straight line across the diameter of the bit with a thickness of 3 mm. In the model, the teeth are assumed to be arranged in a circle having the circumference of the same length as the straight line and with the same thickness. This modification makes the teeth shape compatible with the axisymmetric model and maintains the same contact area with the rock.

In the simulation, the ball is hitting the shaft of the bit with a speed of 3 m/s. The corresponding energy is 1.0 J. Figure 7 shows the displacements of the ball and the bit shaft. The contact time is ~125 μs and the bounce back speed was calculated as 1.83 m/s. The forces at the ball-bit and the bit-rock interfaces are presented in Figure 8. The maximum ball impact force reaches 16.7 kN at time of ~50 μs. The impact creates an elastic wave that is propagating down into the rock. The maximum force at the bit-rock interface is up to 22.1 kN (65 MPa averaged stress) at ~280 μs. This stress itself should fracture the rock at the bit interface assuming a rock of medium hardness.

Figure 6: The FE model of the drill bit and auger that is impacted by a ball.

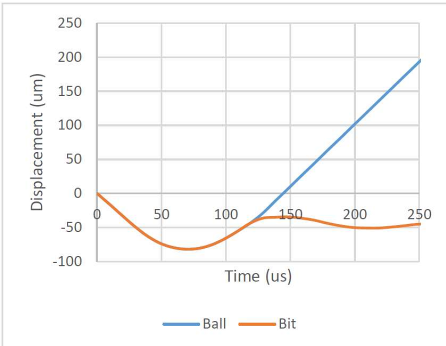


Figure 7: The displacement of the ball and bit shaft after impact

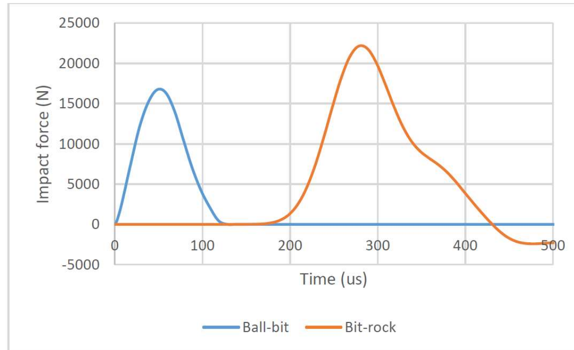


Figure 8: The force at the ball-bit and bit-rock interfaces

5. PIEZOELECTRIC TRANSDUCER DRIVE ELECTRONIC DEVELOPMENT

Testing of the developed driver electronics proved that it is very robust. However, the firmware used by the PCB's microprocessor continues to be upgraded with faster sweep routines, better frequency read-back and more precise fusing. The C++ Lab GUI with MODBUS/RS485 COM was also upgraded in parallel with the firmware to aid in the actuator testing (Figure 9). This GUI however will be replaced with the Beaglebone Ethernet/RS485 system.

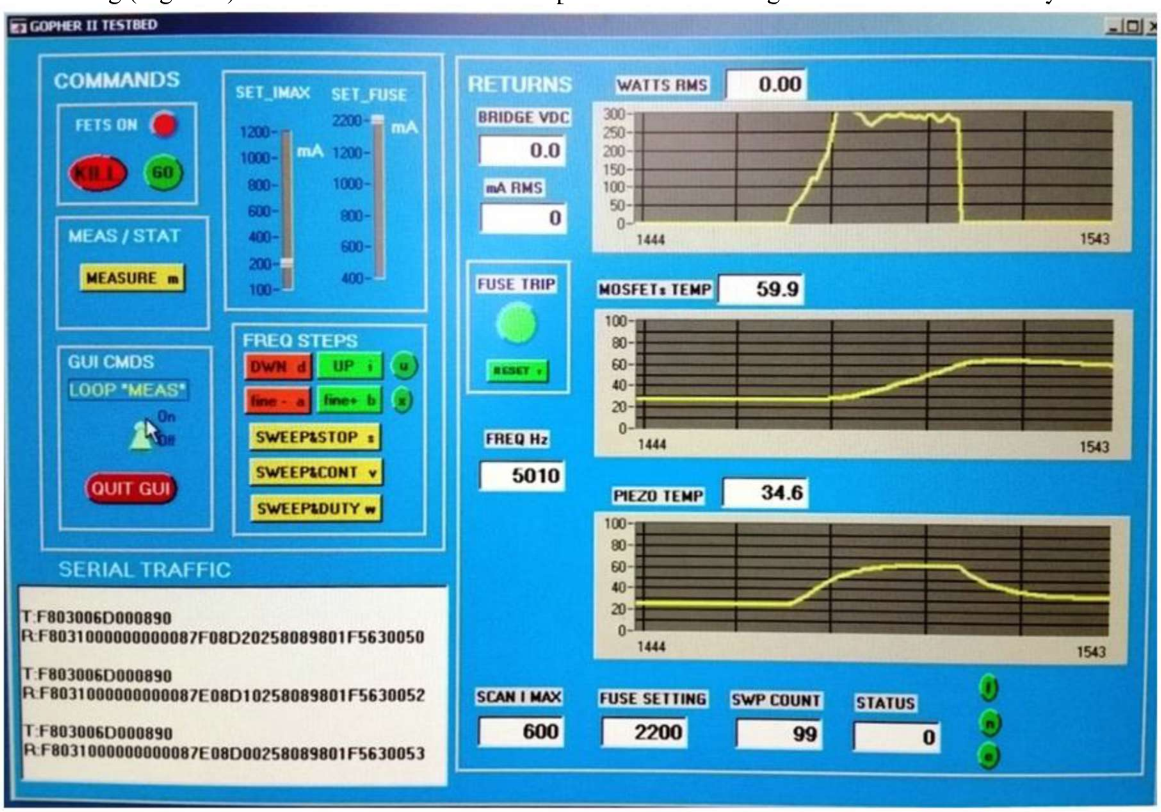


Figure 9: C++ Lab GUI displaying MODBUS Serial traffic after 300W RMS run. MOSFETs ran without heat sinking to test worst-case conditions.

The Driver has now been used for dozens of actuator tests at powers up to 300W RMS. Some anomalies in the output current wave shapes were investigated leading to part change-outs, like MOSFETs and bias components. After significant testing, the electronics did prove to be operating correctly. A second Driver PCB was populated, programmed and calibrated for MODBUS software design use at JPL. Another driver PCB has been delivered to Honeybee Robotics where a third PCB is also under construction. A high voltage opto-isolated relay, which will be packaged in the PCB enclosure, was modified for slow turn-on to prevent unwanted current surges.

An investigation was done on tracking down an asymmetry seen in the current waveform of the transducer. Using the circuit equivalent model of the piezoelectric stack a PSPICE simulation was made to look at different aspects of the drive circuit and its interaction with the piezoelectric model. The left and right pictures in Figure 10 show good agreement between the PSPICE model and data collected from the electronics at low transducer power levels.

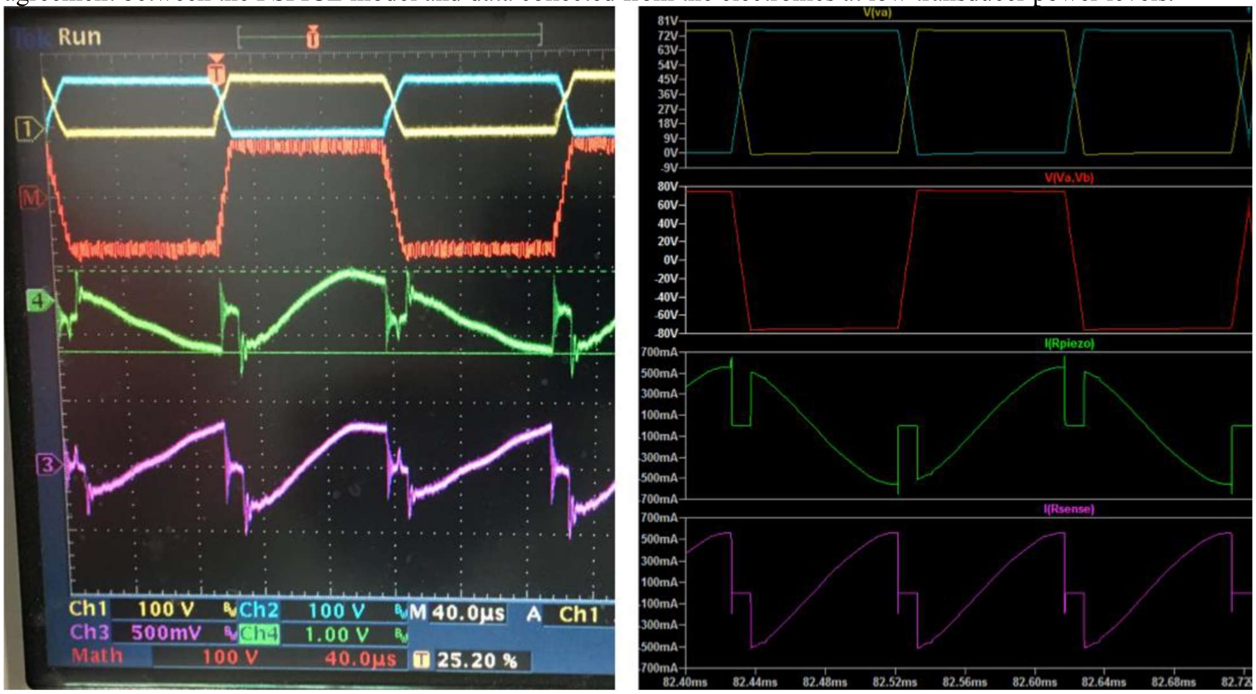


Figure 10: (Left) Oscilloscope waveforms from transducer. (Right) PSPICE simulation of the same drive voltages

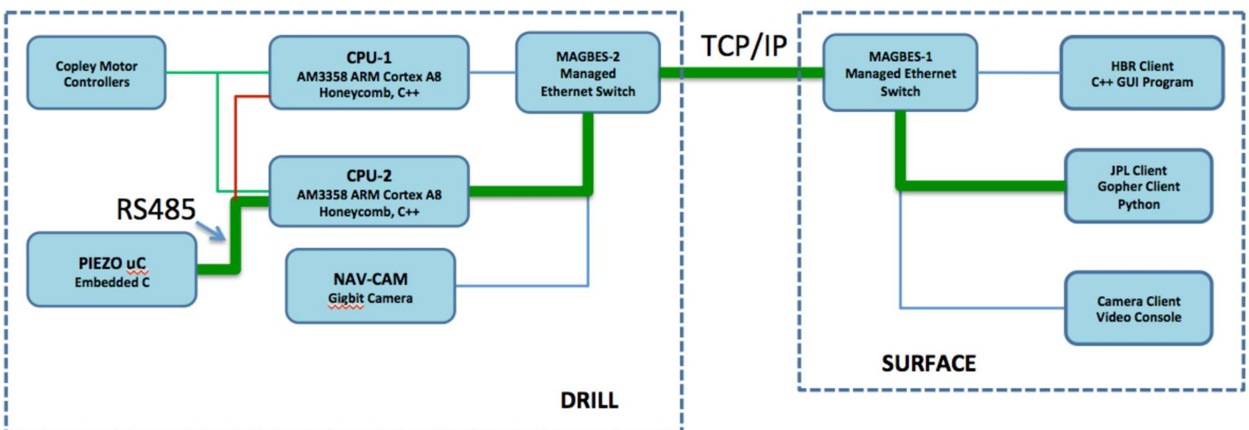


Figure 11: Communication Overview, successful communication from surface client to drill piezoelectric driver.

A communication overview schematic is shown in Figure 11 for the gopher II command and control. Successful communication from the JPL client to the embedded piezoelectric microcontroller using the proper channels of TCP/IP to RS485 was accomplished. The JPL client is a Gtk GUI utilizing a gopher library that was written in Python to allow easy portability and platform independence. The python library uses the ZeroMQ messaging protocol to communicate with the gopher server located in the drill over TCP/IP. The gopher server located on the AM3358 platform inside the drill communicates over two ports including a subscriber based model on one port, and a request and reply model on the second port. The publisher broadcasts the event records of commands received, Modbus communication, and other diagnostic information to clients that have subscribed to the server. This allows status to be broadcast across multiple devices, where the failure of one client does not take down the remaining subscribers. The request and reply portion of the server receives commands from a client, executes the command, and replies with the result of that command.

CONCLUSIONS AND FUTURE WORK

In this paper we presented the current state of development of the piezoelectric transducer for the Auto-Gopher II, including the drive electronics, and the analysis of integration with an auger drill bit. A 5 kHz transducer was designed, parts were fabricated and assembled and preliminary testing using lab drive electronics and task developed drive electronics and control software. While the transducer performed well in initial testing its performance decreased in time and investigation is underway to determine the reason for this behavior. Drive electronics and control and communication software for driving the transducer and exchange information with the rest of the drill system were developed and integrated in the Honeybee Robotics developed drill system.

We will continue modify the current the transducer, and when satisfied with its capability integrate it with the lab testbed and test with the developed drive electronics. After these preliminary tests are completed the current version of the hardware and drive electronics will be integrated into the drill system at Honeybee Robotics, Ltd.

Acknowledgements

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